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(19)

(54) IMPROVEMENTS IN OR RELATING TO THE DIRECTIONAL DRILLING OF BOREHOLES

(71) I, ANTHONY WILLIAM RUSSELL, a British Subject, of 265, Old Bath Road, Cheltenham, (formerly of King's House, School Road, Charlton Kings, Cheltenham), do hereby declare the invention, for which I pray that a patent may be granted to me, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to the directional drilling of boreholes and provides improved methods of and means for determining the orientation of a drill head in a borehole to facilitate steering of the drilling tool.

The invention is particularly but not solely applicable to deep drilling with a turbine-driven drilling tool known as a mud-motor which can be steered, to follow a desired path, provided that the existing path of the borehole is known and the orientation of the mud-motor can be ascertained. To provide information on the existing path of the borehole various methods of measuring the azimuth and pitch angles of the borehole are in use. In one such method, known as the single shot method, measurements of azimuth and pitch at the lower end of the borehole are taken during intervals between drilling runs.

Measurement of the orientation of the drill head in the borehole has in the past necessitated the inclusion, in the borehole probe of the instrument, of gravitational field sensors for the determination of the roll angle. For high angle holes, that is boreholes departing largely from the vertical so that the pitch angle is large, it is a practice to base the steering on a roll angle, measured with respect to a gravitational reference, the roll angle measurements being referred to as "high-side" readings. For low angle or near-vertical holes, on the other hand, steering is commonly based on readings of magnetic bearings in a gravitational coordinate system and directly or indirectly involving the high-side angle. It is an aim of the present invention to provide for continuous reading of the orientation during the actual drilling of a borehole whether it be of high angle or low angle, and without the need for gravitational field measurement during the drilling.

The invention in one aspect resides in a method of determining at a drilling station the orientation of a drill head in a borehole comprising the steps of sensing at the location of the tool in the borehole the earth's magnetic field strength components in two of three principal tool axes, the third fixed tool axis being the borehole axis, signalling the sensed field strengths to the drilling station and relating said sensed field strength components to the inclination and bearing of the lower end of the borehole.

In carrying out the invention the sensed components are translated according to the direction and inclination of the borehole axis. The translation is preferably effected by relating the sensed components to the earth's magnetic field components in principal axes rotated from magnetic north by the azimuth angle of the borehole axis and from the vertical by the pitch angle of the borehole axis.

The method involves the transfer of angles or vectors between two sets of axes, namely the fixed tool axes and fixed earth axes. Data for transferring the earth's magnetic field components at the drilling station to angularly rotated coordinates may be calculated and stored in graphs or tables, or otherwise, and selectively applied in the computation of the tool orientation from particular sets of sensed field strengths signalled to the drilling station. In this way, a particular computation becomes a simple matter and can be done by means of an electromechanical resolver or comparable device with an appropriately calculated or selected angle addition to its indicated angle reading.

The invention also resides in a method of steering a drilling tool in a borehole by remote control from a drilling station, wherein the drill head orientation is determined as described above and periodically or continuously indicated during a drilling run.

The invention also comprises means for

determining the orientation of the drill head by the method set out above.

In one particular form the invention provides a measuring device comprising a bore-hole unit having two static sensors for measuring the magnetic field strength in two directions at right angles to each other and fixed in relation to the body of the unit, and means for transmitting the measurements to a surface indicator unit, the latter having signal processing circuits for deriving and displaying directional information and means for injecting into the processing circuits angle information based on the local values of the earth's magnetic field.

The invention provides steering parameters during the actual process of drilling, which parameters are derived only from magnetic sensors and available single shot measurements relating to the borehole. The need for gravity sensors in the orientation determining equipment is obviated.

A compass comprising static sensors fixed to the drill head to indicate remotely the bearing orientation of the tool when the tool is vertical, that is in a vertical borehole, will indicate, when the tool is inclined, a drill orientation in a different reference system. When the tool is vertical the reference system is defined by the three principal axes V, N and E. The magnetic datum direction is magnetic North at the geographical site and constitutes in effect the zero setting for an indicator or a protractor on a topographical chart. The primary tool axis is vertical and the tool orientation is the roll angle ϕ of each of the other two fixed tool axes in the horizontal plane and with respect to N and E respectively. When the tool is inclined the reference system has principal axes inclined respectively to V, N and E, one of these principal axes being still the primary tool axis and the measurements being made in the other two fixed tool axes but in terms of earth magnetic field components in the direction of those two axes, which components are not simply geometrically related to North and East magnetic field components but depend not only on the geographical site but also on the extent of the inclination. It will be shown that the measured orientation angle in the different reference system can nevertheless be translated into either a bearing orientation with respect to magnetic North (useful when the inclination is small), or an orientation about the tool and borehole axis, (i.e. the roll angle ϕ, useful for high angle holes), that is, into a useful orientation angle in the V, N, E reference system or in the reference system defined by the principal tool axes, by the simple introduction of a computed datum angle and hence by providing for a computed or precalibrated zero setting of the compass indicator.

The determination of the orientation of a drilling tool, specifically a mud-motor, in accordance with the invention will now be described in more detail, and specific forms of equipment embodying the invention will also be described with reference to the accompanying drawings, in which:—

Figure 1 is a diagram showing the earth fixed axes and the tool fixed axes,

Figures 2, 3 and 4 illustrate three successive rotations relating the earth axes to the tool axes,

Figure 5 is a diagram representing the bottom of the borehole,

Figure 6 shows diagrammatically a read-out resolver servo to which signals from crossed magnetic sensors are applied,

Figure 7 is a block diagram of the preferred system,

Figure 8 shows equipment suited to the system of Figure 7,

Figures 9 and 10 show successive resolver arrangements in the system of Figure 7,

Figures 11, 12 and 13 are block diagrams illustrative of alternative methods of computing pre-set angles,

Figure 14 is a circuit diagram for analogue computation of required modifying angles, and

Figure 15 illustrates equipment alternative to that of Figure 8.

The method assumes the availability of single shot readings relating to the borehole immediately prior to a tool run and provides during the tool run high-side and/or magnetic readings of the tool face orientation from the outputs of just two magnetic sensors. The equipment described is effective for hole directions differing by more than about 5° from the direction of the resultant magnetic field of the earth at the hole location. For smaller angles a complementary high-side tool may be used, but since the number of occasions for such use is small it suffices to hold a small number of such high-side tools for issue and use in the field as required.

Geometric considerations call for rotations from the earth fixed axes into the tool fixed axes involving the azimuth angle ψ, the pitch angle θ and the roll angle ϕ.

Referring to Figure 1, in which 10 represents the borehole, the earth fixed axes are defined as follows:—

ON Horizontal North,
OE Horizontal East,
OV Vertical Down.

The tool fixed axes are defined as follows:—

OX Perpendicular to the Hole axis and defining the T-Head direction,
OY Perpendicular to the Hole axis and perpendicular to T-Head direction,
OZ Hole axis.

The earth-fixed set of axes rotate into the tool-fixed set of axes via the following clockwise rotations: —

(a) Rotation about OV through the *azimuth angle* ψ as shown in Figure 2. A vector $\overline{V}$ with components V_N along ON, V_E along OE and V_V along OV will have components V_{N1} along ON_1, V_{E1} along OE_1 and V_V along OV, where

$$V_{N1}=V_N \cos\psi+V_E \sin\psi,$$
$$V_{E1}=-V_N \sin\psi+V_E \cos\psi.$$

(b) Rotation about OE_1 through the *pitch angle* θ as shown in Figure 3. The vector $\overline{V}$ with components V_{N1} along ON_1, V_{E1} along OE_1 and V_V along OV will have components V_{N2} along ON_2, V_{E1} along OE_1 and V_Z along OZ, where

$$V_{N2}=V_{N1} \cos\theta-V_V \sin\theta=V_N \cos\theta \,.\, \cos\psi+V_E \cos\theta \,.\, \sin\psi-V_V \sin\theta,$$

$$V_Z=V_{N1} \sin\theta+V_V \cos\theta=V_N \sin\theta \,.\, \cos\psi+V_E \sin\theta \,.\, \sin\psi+V_V \cos\theta.$$

(c) Rotation about OZ through the *high-side angle* ϕ as shown in Figure 4. The vector $\overline{V}$ with components V_{N2} along ON_2, V_{E1} along OE_1 and V_Z along OZ will have components V_X along OX, and V_Y along OY, and V_Z along OZ, where

$$\begin{aligned}V_X&=V_{N2} \cos\phi+V_{E1} \sin\phi\\&=V_N(\cos\phi \cos\theta \cos\psi-\sin\phi \sin\psi)+V_E(\cos\phi \cos\theta \sin\psi+\sin\phi \cos\psi)-V_V \cos\phi \sin\theta,\end{aligned}$$

$$\begin{aligned}V_Y&=-V_{N2} \sin\phi+V_{E1} \cos\phi\\&=V_N(-\sin\phi \cos\theta \cos\psi-\cos\phi \sin\psi)+V_E(-\sin\phi \cos\theta \sin\psi+\cos\phi \cos\psi)+V_V \sin\phi\sin\theta,\end{aligned}$$

$$V_Z=V_N \sin\theta \cos\psi+V_E \sin\theta \sin\psi+V_V \cos\theta.$$

If θ and ψ are known from a prior single shot measurement and do not change significantly during the course of a tool run, then measurements of B_x and B_y can yield either the high-side parameter ϕ required for high angle holes or the magnetic parameter $\psi+\phi$ required for low angle holes, since B_v/B_h will be known for any particular location. The manner of extracting these parameters will be described with reference to Figure 5 which represents a cross-section of the hole bottom where the hole direction, prior to renewed drilling, is surveyed to yield pitch angle θ and azimuth angle ψ. ϵ, the angle between the high-side direction and the direction of the component of the earth's magnetic field $\overline{B}$ in this plane, is a function of θ, ψ and the magnetic dip angle δ at the site. This function can be calculated prior to the tool run. Magnetic sensors along the tool-fixed axes yield values $K.B_x$ and $K.B_y$ where B_x and B_y are the components of $\overline{B}$ in the tool-fixed axes directions and K is a constant. If $K.B_x$ and $K.B_y$ are fed into the readout unit resolver servo shown in Figure 6, the readout pointer and scale yield angle r, where

$$\frac{\sin r}{\cos r}=\frac{-B_y}{-B_x}.$$

Thus, $r=-\gamma$.

The required high-side angle

$$\phi=\epsilon-\gamma=\epsilon+r$$

can be obtained in any one of three ways as follows: —

(a) Read angle r on readout scale and add ϵ to this reading to obtain ϕ.

(b) Rotate the readout outer scale counterclockwise with respect to the pointer through angle ϵ prior to drilling. The readout pointer/scale reading will then yield ϕ directly.

(c) Rotate the readout pointer clockwise with respect to the outer scale through angle ϵ prior to drilling. The readout pointer/scale reading will then read ϕ directly. In the preferred system described hereafter, method (c) is carried out by rotating the vector components $K.B_x$ and $K.B_y$ through angle ϵ prior to feeding them into the readout resolver servo.

The magnetic steering parameter can be obtained in a similar manner by adding a correction ϵ', where ϵ' is again a function of θ, ψ and δ.

The arrangement in Figure 6 is a conventional electro-mechanical resolver servo unit comprising a motor 61 fed by a resolver 62 through an amplifier 63 and coupled to the resolver through a reduction gear 64 and a coupling 65 to rotate the resolver 62 through an angle indicated on a scale 66 by a pointer 67 when electrical signals representing the sine and cosine of that angle are applied to appropriate resolver input connections 68 and 69.

A block diagram of the preferred system is shown in Figure 7, and a pictorial view showing a convenient arrangement of the parts of the system is shown in Figure 8. OX and OY sensors 71 and 72 at the location of the drilling tool in the borehole deliver signals

V_{BX} and V_{BY} to transmission means 73, whereby the said signals are fed to a resolver unit 74 at the surface drilling station from which modified signals $V_{BX}1$ and $V_{BY}1$ are applied to a readout unit 75 to indicate the required angle *r*.

In the preferred form of tool steering equipment, that is, orientation determining equipment to assist in steering, shown in Figure 8, the downhole assembly 81 is located by guides 82 in a fixed attitude with respect to the T-slotted head 83 of the mud-motor and contains two magnetic flux gates 84, 85 mounted (usually aligned with the T-slot) in such a way that their sensitivity axes are the OX and OY axes of the previous discussion. This assembly 81 also houses associated signal processing circuitry 86 to allow transmission by a conventional pulse modulation technique through a single conductor 87 in a protective sheath 88 providing a ground return path. The surface equipment comprises a unit 89 containing a power supply sub-assembly 90, pulse reception and signal recovery circuitry in a sub-assembly 91 and computation circuitry in a sub-assembly 92. The angles ψ and θ are set up on dials 93 and 94 respectively for the feeding of the angle information to the computation circuitry. The unit 89 further comprises a read-out unit 96 in the form of a resolver servo 97 and an indicating dial 98. A meter 99 which indicates the strength of the earth's magnetic field in the measuring plane BOXY is located in the unit 89. The meter 99 indicates the calculated field value supplied by the computation circuit sub-assembly 92 and also, simultaneously or alternatively for comparison, the measured field value supplied by the resolver servo 97 over a connection 100.

Principle of Operation

The components of the earth's magnetic field in the directions of the previously defined earth-fixed axes are as follows:—

B_H in direction ON (North),
Zero in direction OE (East),
B_V in direction OV (Vertically down).

Thus, the components of the earth's magnetic field in the direction OX and OY of the previously defined tool-fixed axes will be as follows:—

$$B_X = B_H(\cos\phi\cos\theta\cos\psi - \sin\phi\sin\psi) - B_V\cos\phi\sin\theta \quad (1)$$
in direction OX,

$$B_Y = -B_H(\sin\phi\cos\theta\cos\psi + \cos\phi\sin\psi) + B_V\sin\phi\sin\theta \quad (2)$$
in direction OY.

As represented in Figure 9, voltage analogues $V_{BX}=K.B_X$ and $V_{BY}=K.B_Y$ which are derived from the downhole probe sensors are passed into the resolver which is preset at angle ε, where

$$\sin\varepsilon = -P.\sin\psi \quad (3)$$

$$\cos\varepsilon = P(\cos\theta\cos\psi - \tan\delta\sin\theta) \quad (4)$$

P and K are positive constants and

$$\tan\delta = \frac{B_V}{B_H}.$$

The value of ε is independent of B_X and B_Y and is derived from a knowledge of the single shot measurements of ψ and θ read immediately prior to the tool run, together with the value of the dip angle δ for the drilling site location. Clearly,

$$\tan\varepsilon = \frac{-\sin\psi}{\cos\theta\cos\psi - \tan\delta\sin\theta} \quad (5)$$

The outputs from this resolver are $V_{BX'}$ and $V_{BY'}$ where, as the result of anticlockwise rotation of V_{BX} and V_{BY} through angle ε,

$$V_{BY'} = V_{BY}\cos\varepsilon - V_{BX}\sin\varepsilon \quad (6)$$

$$V_{BX'} = V_{BY}\sin\varepsilon + V_{BX}\cos\varepsilon \quad (7)$$

$V_{BX'}$ and $-V_{BY'}$ are the inputs to a resolver servo shown in Figure 10 and comprising resolver 101, amplifier 102, motor 103 and reduction gear 104 which drives the readout pointer 105 through a clockwise angle r, where

$$\frac{\sin r}{\cos r} = \frac{-V_{BY'}}{V_{BX'}} \quad (8)$$

The resolver outputs of this unit are zero and V_{BOXY}, where

$$V_{BOXY} = -V_{BY'}.\sin r + V_{BX'}.\cos r = (V_{BX}^2 + V_{BY}^2)^{\frac{1}{2}} \quad (9)$$

From equations (6), (7) and (8)

$$\frac{\sin r}{\cos r}=\frac{-V_{BY}\cos\varepsilon+V_{BX}\sin\varepsilon}{V_{BY}\sin\varepsilon+V_{BX}\cos\varepsilon} \qquad (10)$$

Thus, making use of equations (1) and (2),

$$\frac{\sin r}{\cos r}=\frac{\begin{array}{l}\cos\varepsilon\sin\phi\cos\theta\cos\psi+\cos\varepsilon\cos\phi\sin\psi-\cos\varepsilon\tan\delta\sin\phi\sin\theta\\ +\sin\varepsilon\cos\phi\cos\theta\cos\psi-\sin\varepsilon\sin\phi\sin\psi-\sin\varepsilon\tan\delta\cos\phi\sin\theta\end{array}}{\begin{array}{l}-\sin\varepsilon\sin\phi\cos\theta\cos\psi-\sin\varepsilon\cos\phi\sin\psi+\sin\varepsilon\tan\delta\sin\phi\sin\theta\\ +\cos\varepsilon\cos\phi\cos\theta\cos\psi-\cos\varepsilon\sin\phi\sin\psi-\cos\varepsilon\tan\delta\cos\phi\sin\theta\end{array}}$$

$$=\frac{\begin{array}{l}\sin\phi\,[\cos\varepsilon(\cos\theta\cos\psi-\tan\delta\sin\theta)-\sin\varepsilon\sin\psi]\\ +\cos\phi\,[\sin\varepsilon(\cos\theta\cos\psi-\tan\delta\sin\theta)+\cos\varepsilon\sin\psi]\end{array}}{\begin{array}{l}\cos\phi\,[\cos\varepsilon(\cos\theta\cos\psi-\tan\delta\sin\theta)-\sin\varepsilon\sin\psi]\\ -\sin\phi\,[\sin\varepsilon(\cos\theta\cos\psi-\tan\delta\sin\theta)+\cos\varepsilon\sin\psi]\end{array}}$$

Substitution of equations (3) and (4) leads directly to

$$\frac{\sin r}{\cos r}=\frac{\sin\phi(\cos^2\varepsilon+\sin^2\varepsilon)+\cos\phi(\sin\varepsilon\cos\varepsilon-\cos\varepsilon\sin\varepsilon)}{\cos\phi(\cos^2\varepsilon+\sin^2\varepsilon)-\sin\phi(\sin\varepsilon\cos\varepsilon-\cos\varepsilon\sin\varepsilon)}$$

$$=\frac{\sin\phi}{\cos\phi}$$

Thus, clearly the readout angle r is the high-side angle ϕ.

If the present resolver angle is set at angle ε', where

$$\sin\varepsilon'=-P\,.\,\sin\theta\sin\psi\tan\delta \qquad (11)$$

$$\cos\varepsilon'=P\,.\,(1-\sin\theta\cos\psi\tan\delta) \qquad (12)$$

and P is a positive constant, then for small angles θ this system will yield a readout angle r equal to the magnetic steering parameter m, where $m=\phi+\psi$. Clearly,

$$\frac{\sin r}{\cos r}=\frac{-V_{BY}\cos\varepsilon'+V_{BX}\sin\varepsilon'}{V_{BY}\sin\varepsilon'+V_{BX}\cos\varepsilon'} \qquad (13)$$

Equations (1) and (2) for the small angle θ case become

$$B_X=B_H\cos m-B_V\sin\theta\cos\psi\cos m-B_V\sin\theta\sin m\sin\psi \qquad (14)$$

$$B_Y=-B_H\sin m+B_V\sin\theta\sin m\cos\psi+B_V\sin\theta\cos m\sin\psi \qquad (15)$$

Thus,

$$\frac{\sin r}{\cos r}=\frac{\begin{array}{l}\sin m\,[\cos\varepsilon'(1-\sin\theta\cos\psi\tan\delta)-\sin\varepsilon'\sin\theta\sin\psi\tan\delta]\\ +\cos m\,[\sin\varepsilon'(1-\sin\theta\cos\psi\tan\delta)+\cos\varepsilon'\sin\theta\sin\psi\tan\delta]\end{array}}{\begin{array}{l}\cos m\,[\cos\varepsilon'(1-\sin\theta\cos\psi\tan\delta)-\sin\varepsilon'\sin\theta\sin\psi\tan\delta]\\ -\sin m\,[\sin\varepsilon'(1-\sin\theta\cos\psi\tan\delta)+\cos\varepsilon'\sin\theta\sin\psi\tan\delta]\end{array}}$$

$$=\frac{\sin m(\cos^2\varepsilon'+\sin^2\varepsilon'+\cos m(\sin\varepsilon'\cos\varepsilon'-\cos\varepsilon'\sin\varepsilon'}{\cos m(\cos^2\varepsilon'+\sin^2\varepsilon')-\sin m(\sin\varepsilon'\cos\varepsilon'-\cos\varepsilon'\sin\varepsilon'}=\frac{\sin m}{\cos m}$$

and clearly the readout angle r is equal to the magnetic steering parameter m.

Computation of Preset angles ϵ and ϵ'

The values of ϵ and ϵ' are independant of the sensing probe outputs V_{BX} and V_{BY} and are functions of only the known geometry of the hole pertaining prior to the tool-run and the earth's magnetic field at the site location. There are basically three ways by which the ϵ and ϵ' values can be derived and used for the preset of the resolver operation. All of these ways will involve either directly or indirectly the calculation of ϵ from

$$\tan\epsilon = \frac{-\sin\psi}{\cos\theta\cos\psi - \tan\delta\sin\theta} \qquad (16)$$

and the calculation of ϵ' from

$$\tan\epsilon' = \frac{-\sin\theta\sin\psi\tan\delta}{1-\sin\theta\cos\psi\tan\delta} \qquad (17)$$

These calculations could be performed on a single occasion for each set of ψ, θ and δ and the results could be tabulated and filed for use on all future occasions (Method *a* below). Alternatively, ϵ and ϵ' may be calculated for the appropriate set of ψ, θ and δ values as the occasion demands. The calculations may be done separately prior to each tool run, for example by reference to a computing centre (method *b* below), or they may be done in the computation assembly incorporated in the orientation determining equipment itself (method *c* below).

A block diagram illustrating method *a* is shown in Figure 11. The operator receives the (ψ, θ) set from the single shot measurement taken immediately prior to the tool-run and looks up the corresponding ϵ and ϵ' values in previously computed tables which list all the ϵ and ϵ' values appropriate to the site location for any given (ψ, θ) set. The operator then sets the resolver to either ϵ or ϵ', depending on whether the high-side or the magnetic parameter is required for steering.

A block diagram illustrating method *b* is shown in Figure 12. The (ψ, θ) set from the single shot measurement prior to the tool run is fed either directly or via the operator to a computation centre where the calculation of the corresponding ϵ and ϵ' values is performed (or these values are determined from the results of previous calculations). The computation centre then informs the operator of the ϵ (or ϵ') value to be preset on the resolver.

A block diagram of method *c* is shown in Figure 13. In this method the ϵ, ϵ' computation unit form part of the steering tool equipment. The operator has to perform only the relatively simple task of setting the single shot (ψ, θ) information directly into the on-site equipment. The calculations of ϵ and ϵ' and the resolver preset operation are performed within the tool steering equipment. While method (c) does require that the tool steering equipment will be rather more sophisticated, and hence rather more expensive, it does have the very important advantage of making the task of the operator very much less complicated than in the case of method (a) or method (b).

ϵ or ϵ' Computers

Clearly ϵ and ϵ' could be computed from equations (16) and (17) using a suitably programmed digital computer. However, ϵ and ϵ' are essentially related to vector rotations and can be conveniently computed by an analogue technique. The essential features of the ϵ, ϵ' analogue computer are illustrated in Figure 14. Angles ψ and θ are set up on resolvers 141 and 142 respectively, from which products such as $-B_Y\sin\theta\sin\psi$ can be derived and applied to a resolver servo 143, the resolver 144 of which sets itself to the required angle ϵ or ϵ' and also yields B_{OXY} as an output.

Major advantages of this system are:—

(a) Either high-side or magnetic steering parameters can be chosen through the operation of a 5 pole two-way switch.

(b) The computer outputs ϵ and ϵ' are in the form of a driven shaft rotation which can be used to set the preset resolver directly.

(c) The system also yields the expected value of B_{OXY} which can be compared to the measured value of B_{OXY} (see equation 9) as a system check. The value of B_{OXY} can also be used to warn the operator should he try to operate the tool within the forbidden zone. (Satisfactory operation will not be achieved for hole geometries in which the direction of the hole lies very close to the direction of the earth's magnetic field since V_{BX} and V_{BY} will be very small in this case. These occasions are likely to be very rare).

In the arrangement of equipment shown in Figure 15, method *a* or *b* is used to arrive at the preset angle ϵ or ϵ', and zero setting against an appropriate scale on the indicator is used to introduce the preset angle into the reading.

The downhole assembly 151 is as described with reference to Figure 8. The surface equipment comprises a unit 152 containing reception and signal recovery circuitry, a read-out unit 153 and a meter 154 which indicates the strength of the earth's magnetic field in the measuring plane OXY. The resolver servo 155 is located in the read-out unit. The read-out unit pointer 156 moves over a scale 157 which can itself be rotated about the pointer rotation axis through any given angle.

The operating procedure is as follows:—

(a) The operator acquires the drift and azimuth angles from the most recent single shot run and is instructed by the directional driller as to the requirement for either the

high-side or the magnetic steering parameter.

(b) Using this information, together with the tabulated ε (or ϵ') values for the geographical location of the drilling site, the operator determines the appropriate value of ϵ (or ϵ') and the expected value of the magnetic field strength parameter B_{OXY}.

(c) The operator sets the read-out rotatable scale 157 to the determined value of ϵ (or ϵ').

(d) The tool is then run in the hole and seated repeatedly until three consecutive identical tool face orientations are obtained. The operator also checks the magnetic field strength meter reading with the expected B_{OXY} value.

(e) If (d) is completed satisfactorily, drilling may proceed, and during drilling the necessary steering parameter, either the roll angle ϕ or the magnetic angle $m=\psi+\phi$, is continuously presented to the operator.

(f) As drilling proceeds, the ϵ (or ϵ') value is updated as each set of single shot readings is obtained.

In a typical example of operation, high-side information is required for a tool run on a drilling site at which the earth's magnetic field parameters are $B_h=0.187$ and $B_v=0.434$ (c.g.s.). Single shot measurements immediately prior to the run yield azimuth and drift angles $\psi=S\ 45°W$ and $\theta=15°$ respectively. Thus, the 'fixed' parameters at the time of the run are $\psi=225°$, $\theta=15°$ and $\delta=\tan^{-1}B_v/B_h=66°42'$. For this set of 'fixed' parameters, the corresponding value of ϵ listed in the tables derived from equation 5 is found to be $\epsilon=151°$. This value of ϵ is set on the read-out unit ε scale. From equations (1) and (2), the magnetic field component

$$B_{OXY}=\sqrt{Bx^2+By^2}=\sqrt{b_h^2\,(\cos^2\theta\,\cos^2\psi+\sin^2\psi)+B_v^2\,\sin^2\theta-2B_v\,B_h\,\sin\theta\,\cos\theta\,\cos\psi}$$

and from tables of B_{OXY} based on this equation the value of B_{OXY} corresponding to the set of 'fixed' parameters is found to be $B_{OXY}=0.274$. Operations (a), (b) and (c) have now been completed and operations (d), (e) and (f) may be proceeded with.

WHAT I CLAIM IS:—

1. Method of determining the orientation of the head of a drilling tool in a borehole comprising the steps of sensing at the location of the tool in the borehole vector components of the earth's magnetic field in directions in determined relation to a primary tool axis aligned with the borehole, signalling said vector components from the tool location and relating the signalled components to the known spatial direction of the primary tool axis.

2. Method according to claim 1, wherein the sensed vector components are those in two of three principal tool axes, the third principal tool axis being said primary tool axis aligned with the borehole axis at the tool location.

3. Method according to claim 1 or 2, wherein said signalled components are translated according to the direction and inclination of the borehole axis at the tool location.

4. Method according to claim 2, wherein said signalled components are translated by relating said components to the earth's magnetic field components in principal axes rotated from magnetic north by the azimuth angle of the borehole axes and from the vertical by the pitch angle of the borehole axis.

5. Method according to any preceding claim, wherein the spatial direction of the primary tool axis is the direction of the borehole determined prior to a drilling run.

6. Method according to any preceding claim, wherein the sensed components are signalled by transmitting from the location of the drilling tool signals proportional to said components.

7. Method according to claim 6, wherein said signals are conveyed by a line through the borehole and are received at the drilling station.

8. Method according to any preceding claim, wherein data for transferring the earth's magnetic field components at the drilling station to angularly rotated coordinates is calculated and applied in the computation of the tool orientation from particular sets of sensed components of field strength signalled from the location of the tool.

9. Method according to claim 8, wherein said data is precalculated and stored and selectively applied.

10. Method according to claim 8, wherein said data is calculated and applied automatically to modify the indicated orientation of the tool.

11. Method according to any of claims 1 to 10, wherein the tool orientation is determined as a high side parameter angle ϕ.

12. Method according to any of claims 1 to 10, wherein the tool orientation is determined as a magnetic parameter angle $\psi+\phi$.

13. Method according to any of claims 1 to 10, wherein the orientation is optionally obtainable as either a high side parameter angle ϕ or a magnetic parameter angle $\psi+\phi$.

14. Method of steering a drilling tool in a borehole wherein the orientation of the tool is continuously indicated during a drilling run by the method claimed in any preceding claim.

15. Equipment for carrying out the method of claim 1, comprising magnetic field strength sensors and a signal transmitter associated therewith in a housing attachable in predetermined fixed relation to a drill head, and a computing unit including a receiver cooperat-

ing with said transmitter, a resolver operatively coupled to the receiver to indicate an angle dependant upon sensor information, and means to change the angle indication of the resolver by a preset amount.

16. Equipment for carrying out the method of claim 1, comprising magnetic field strength sensors and a signal transmitter associated therewith in a housing attachable in predetermined fixed relation to a drill head, and a computing unit including a receiver cooperating with said transmitter, a resolver operatively coupled to the receiver to indicate an angle dependant upon sensor information, means for computing a datum angle dependant on the location of the borehole and the inclination of the lower end of the borehole, and means for presenting the indicated angle with respect to the datum angle.

17. Equipment for indicating the orientation of a drill head in a borehole, said equipment comprising a remote reading compass having a sensing unit attachable in predetermined relationship to a drill head, and a computing and indicating unit adapted to be connected to the sensing unit to provide angle indications at a drilling station derived from signals from the sensing unit attached to the drill head in the borehole, the sensing unit comprising static electromagnetic sensors disposed in relation to the tool axes to yield in the computing and indicating unit the angle defining the tool orientation in the frame of reference of the tool axes, and means for zero setting the angle indicator according to a datum angle dependant on the site of the drilling station and the inclination of the borehole at the drilling tool location.

18. A remote reading compass comprising fixed sensors adapted to be attached in fixed relation to a drill head and an indicator for use at the drilling station, the indicator having zero setting graduations in terms of ϵ and/or ϵ' as defined in Equations 16 and 17 to provide for direct indication of the roll angle and/or the bearing orientation of the drilling tool.

19. A remote reading compass according to claim 18, wherein the indicator is a resolver.

20. Method of or means for determining the orientation of a drill head in a borehole substantially as herein described with reference to the accompanying drawings.

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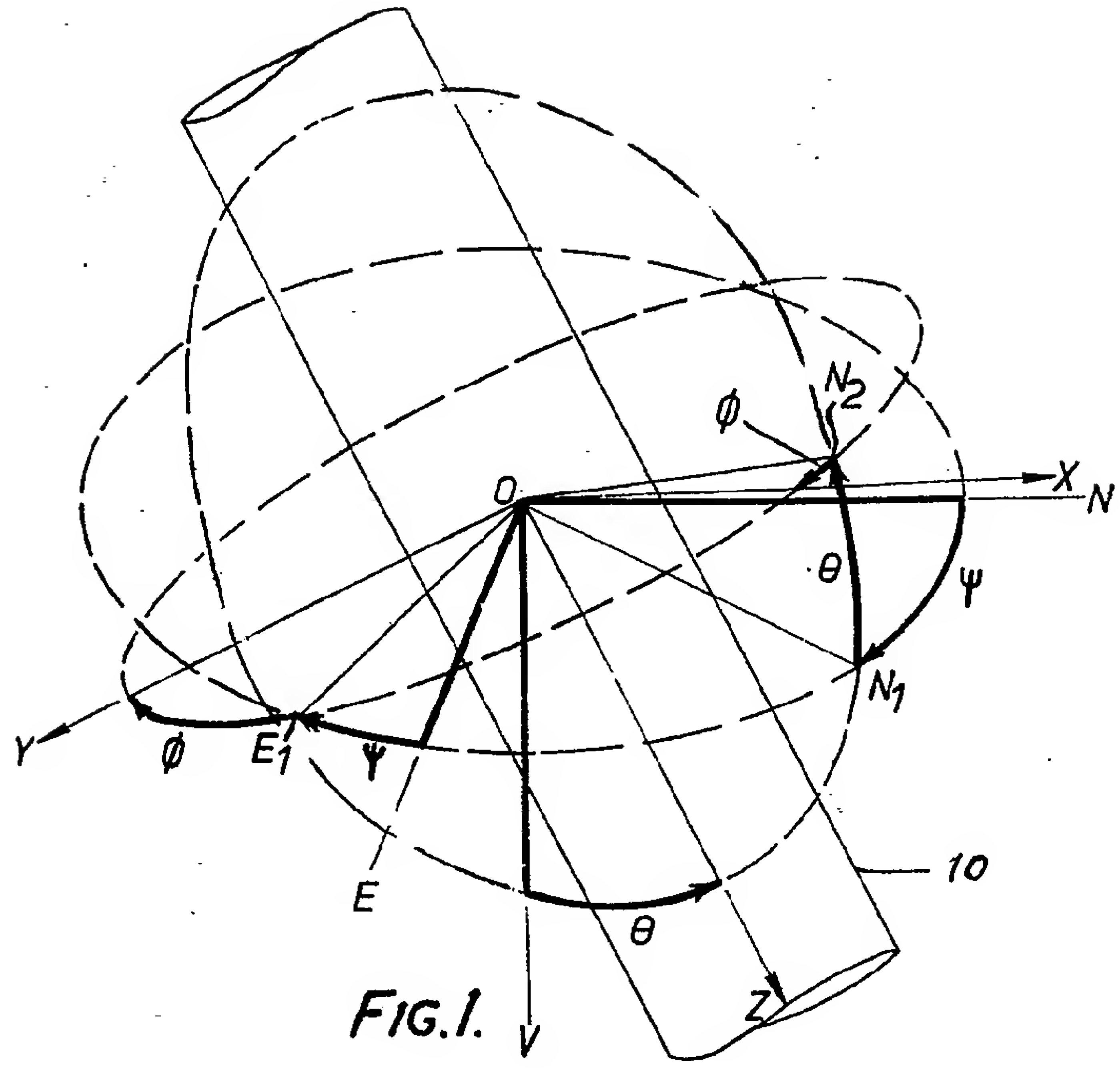

FIG.1.

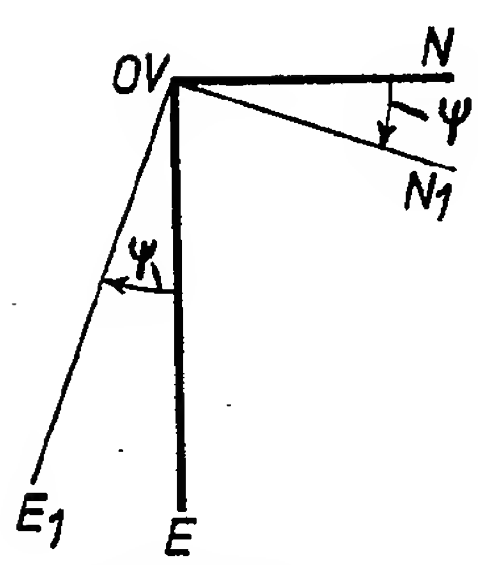

FIG.2.

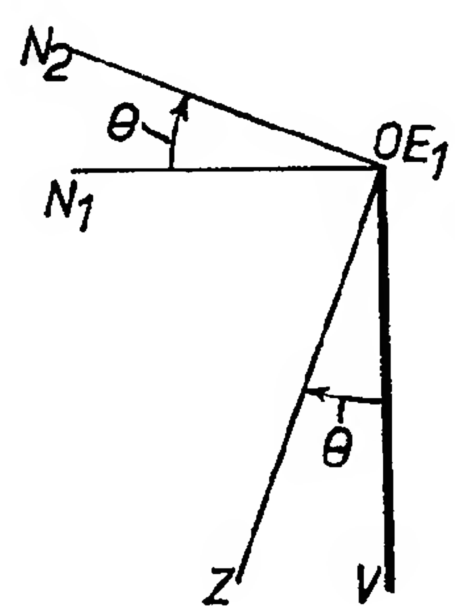

FIG.3.

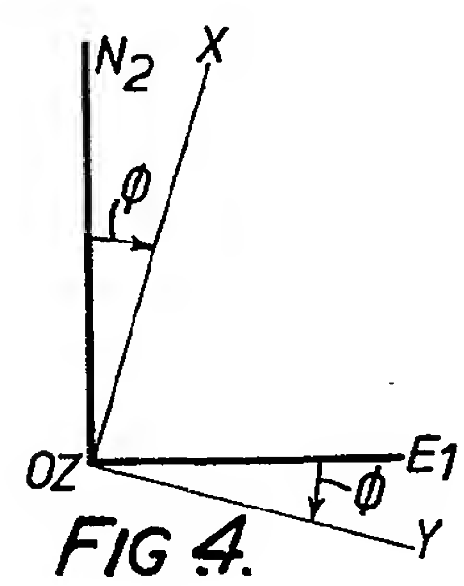

FIG 4.

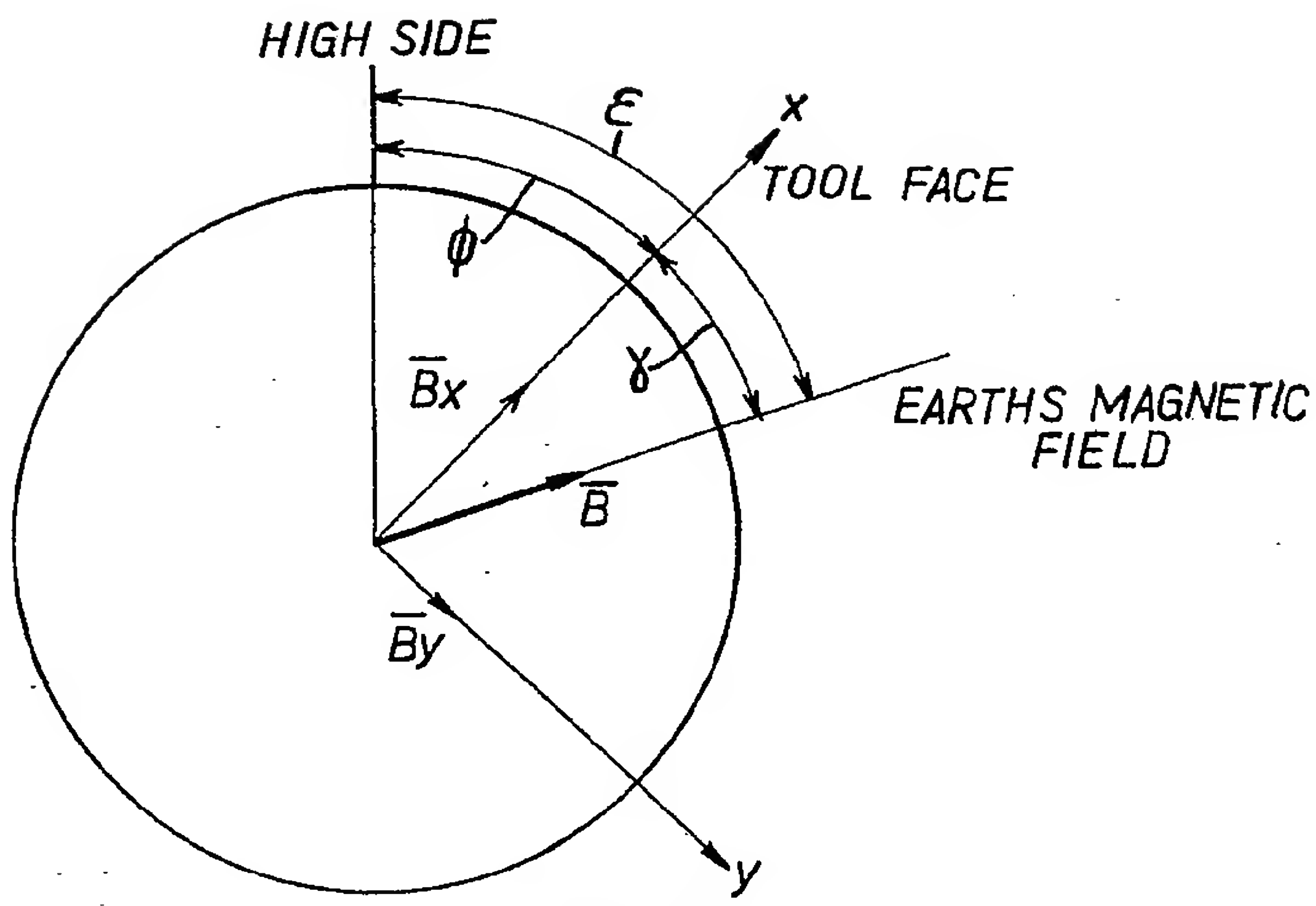
HIGH SIDE
ε
x
TOOL FACE
φ
Bx
γ
EARTHS MAGNETIC FIELD
B
By
y

FIG. 5.

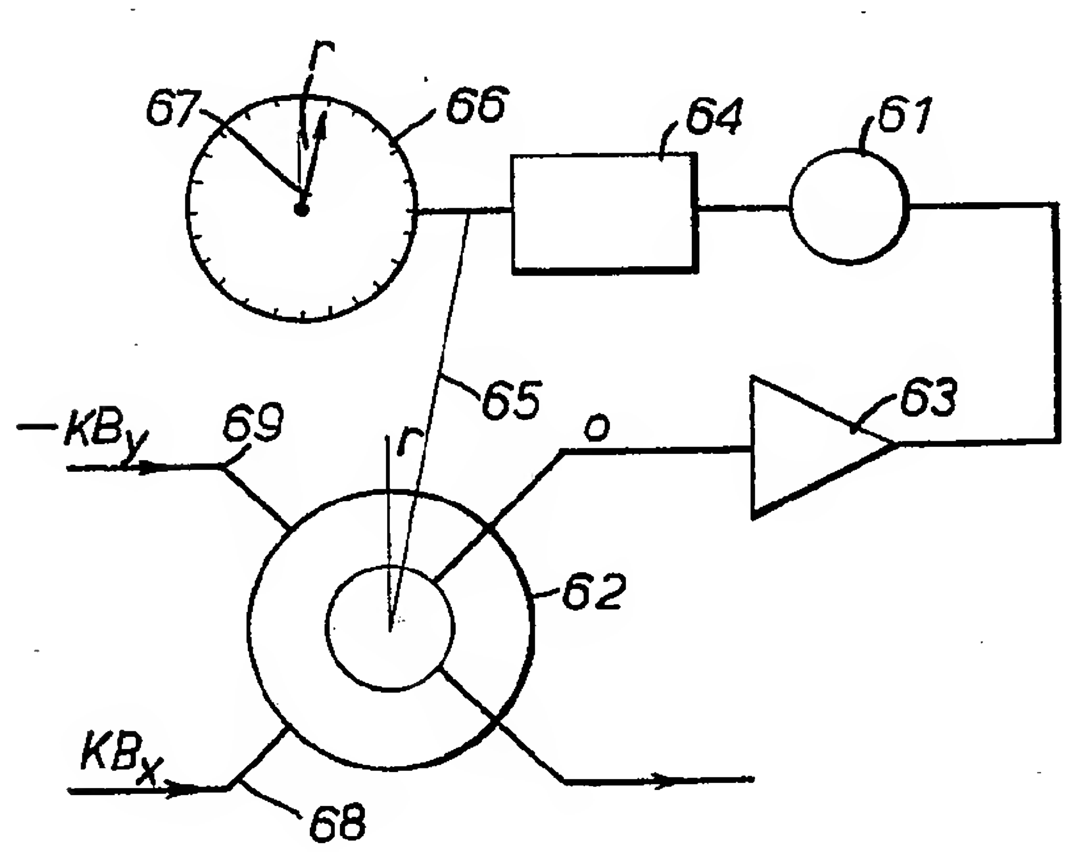
r
67
66
64
61
−KBy
69
65
o
63
r
62
KBx
68

FIG. 6.

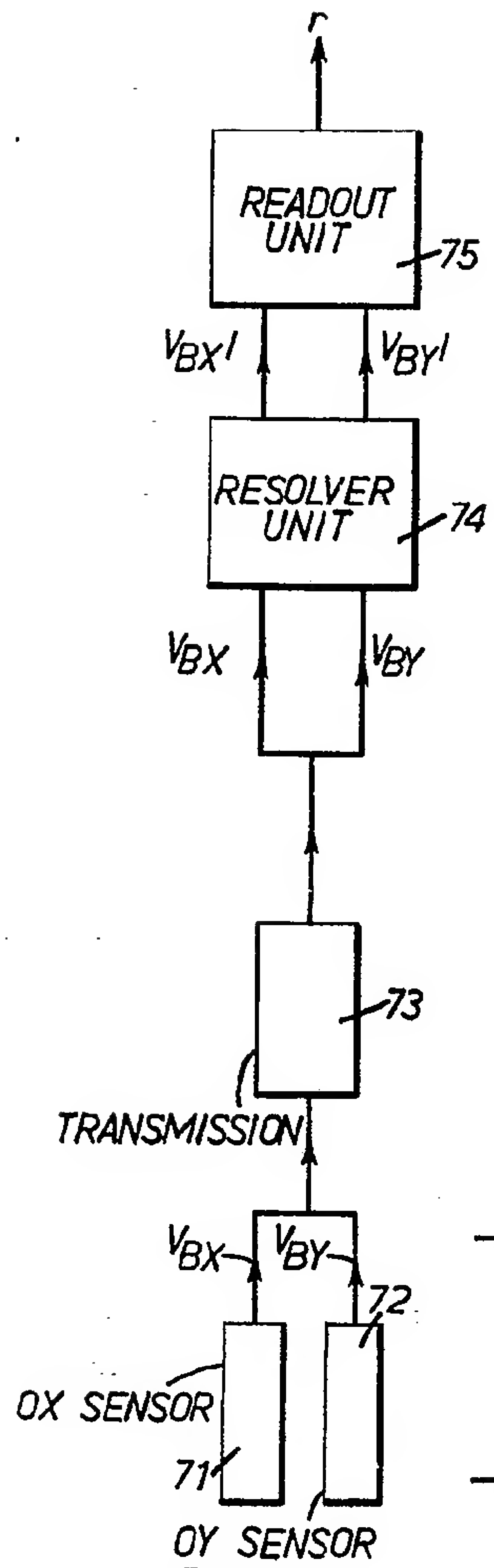

FIG. 7.

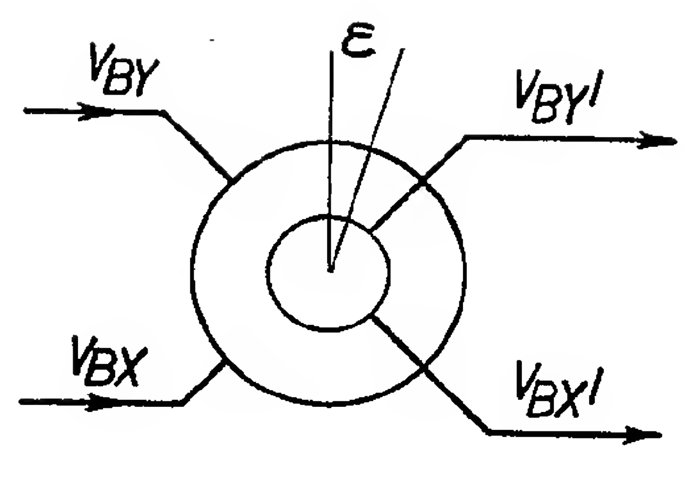

FIG. 9.

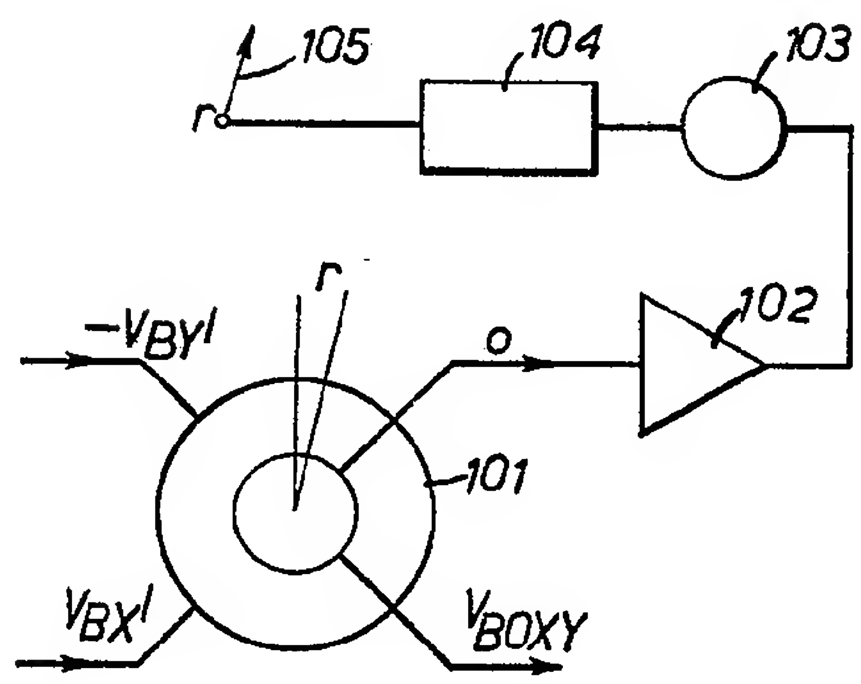

FIG. 10.

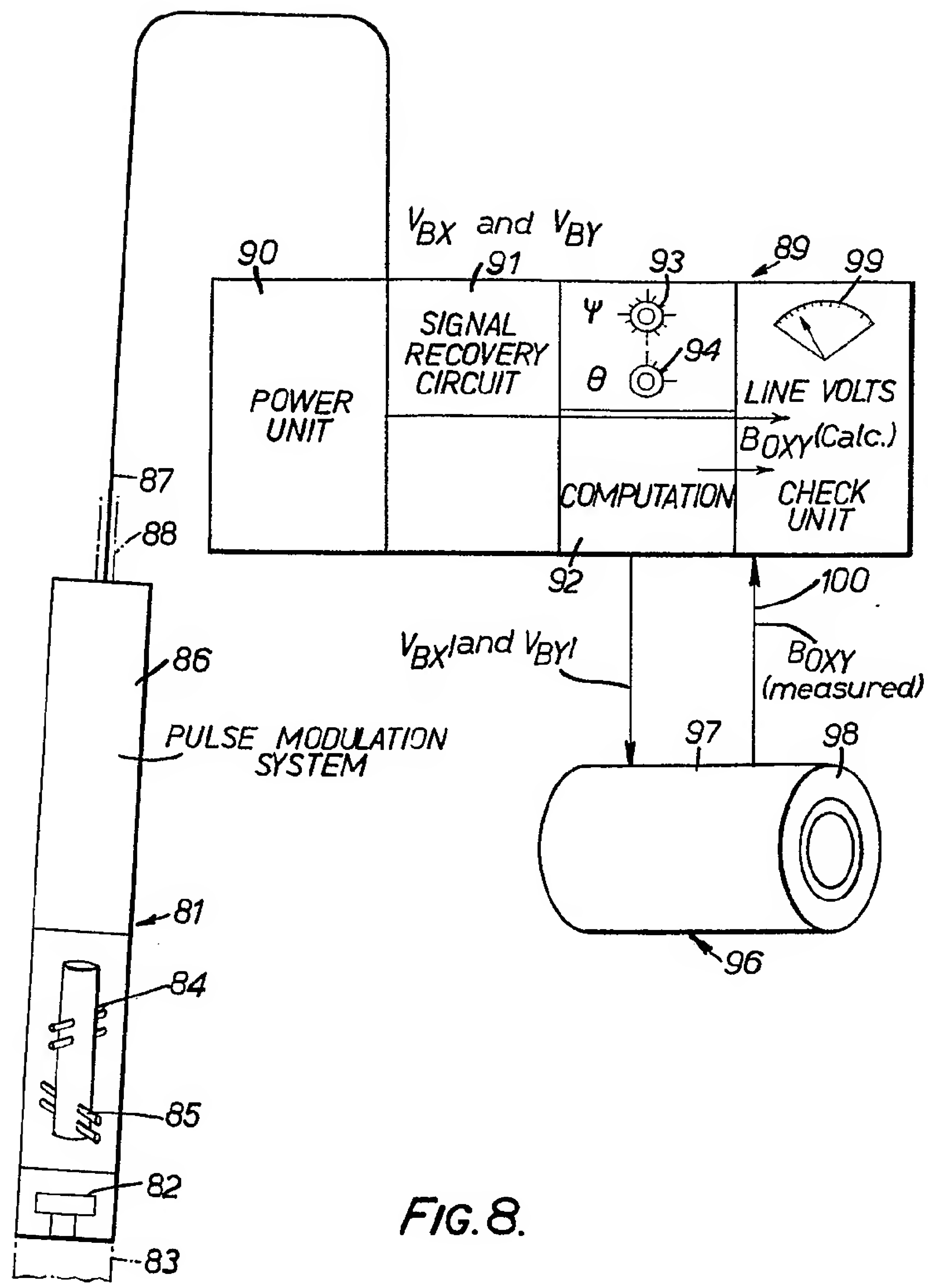
V_{BX} and V_{BY}
90
91
93
89
99
POWER UNIT
SIGNAL RECOVERY CIRCUIT
Ψ
θ
94
LINE VOLTS
B_{OXY}(Calc.)
COMPUTATION
CHECK UNIT
87
88
92
100
86
V_{BX}/and V_{BY}/
B_{OXY} (measured)
PULSE MODULATION SYSTEM
97
98
81
96
84
85
82
83

FIG. 8.

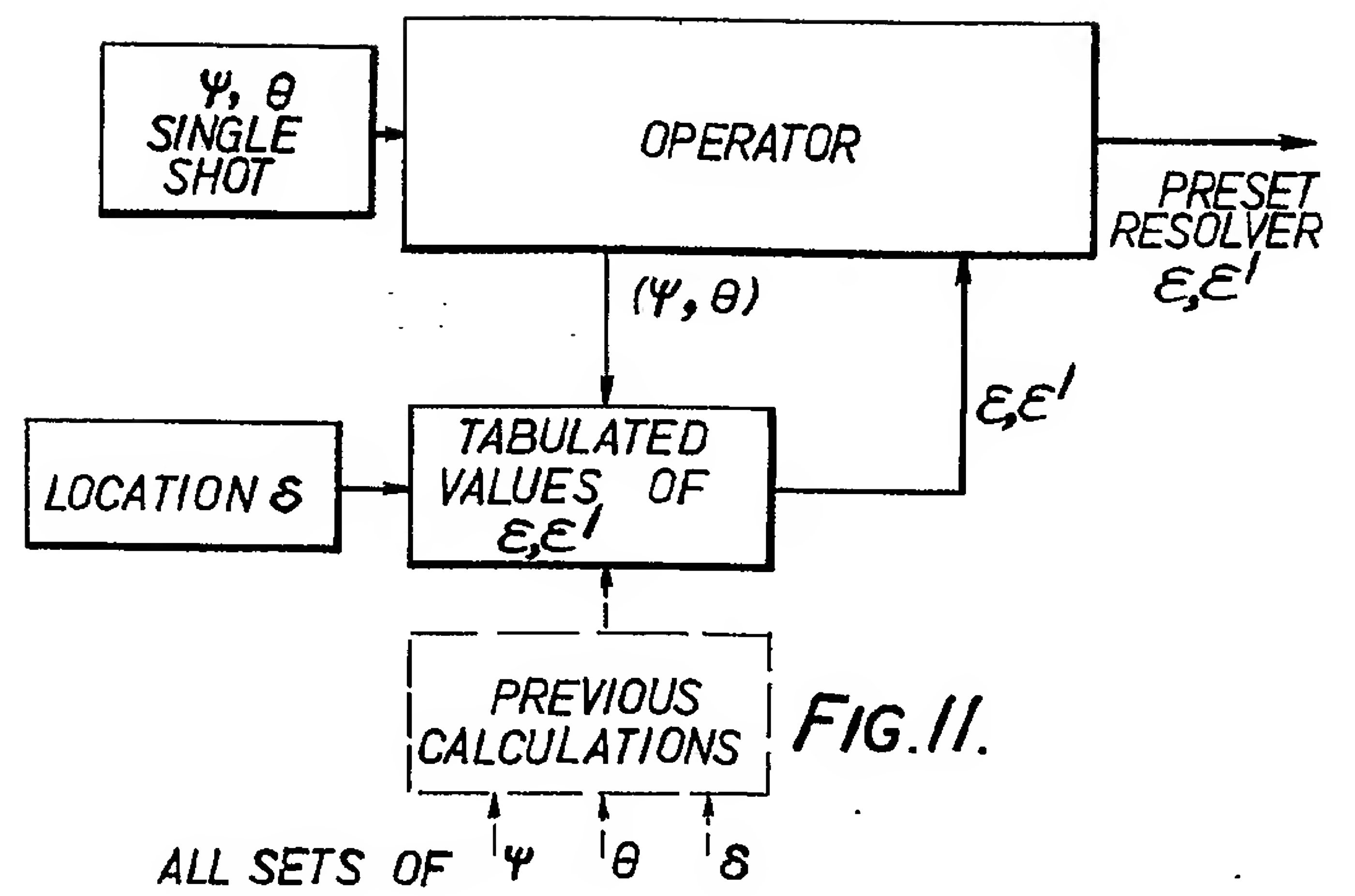

FIG. 11.

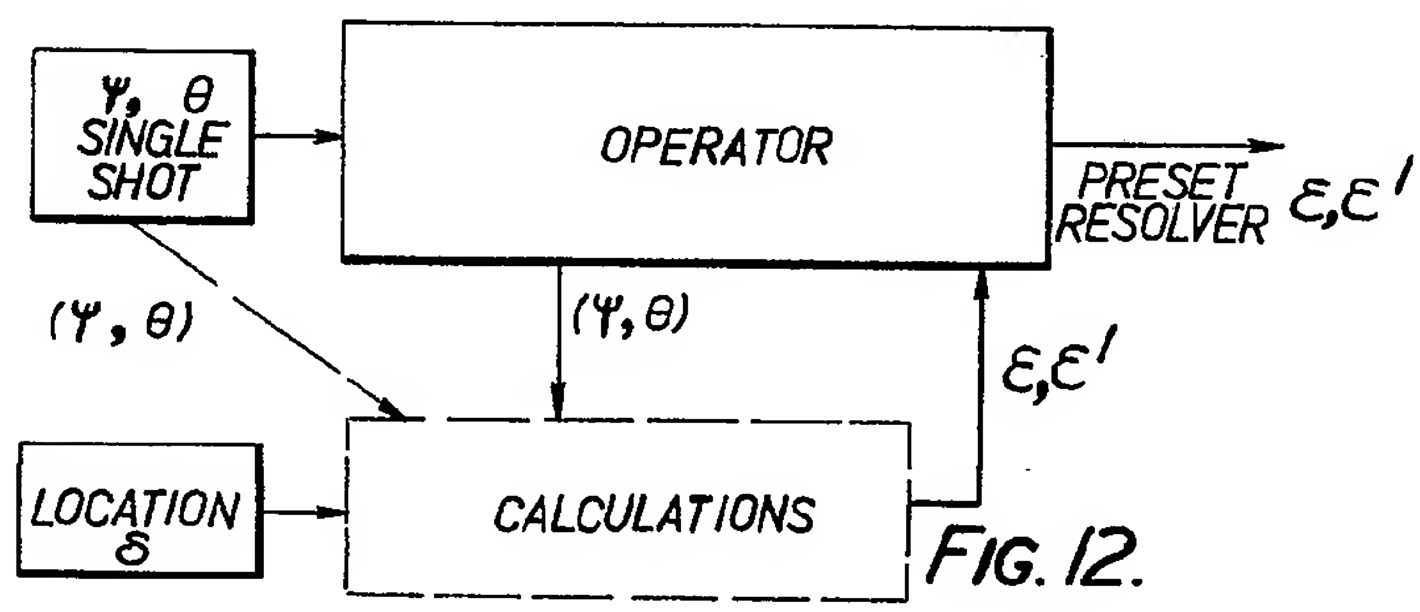

FIG. 12.

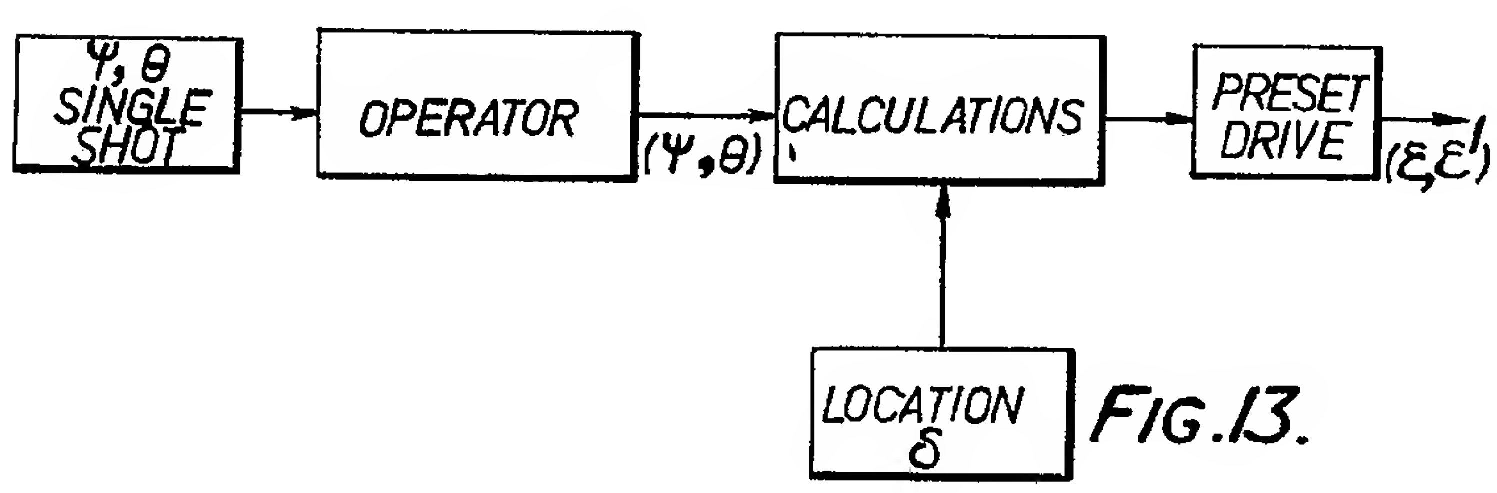

FIG. 13.

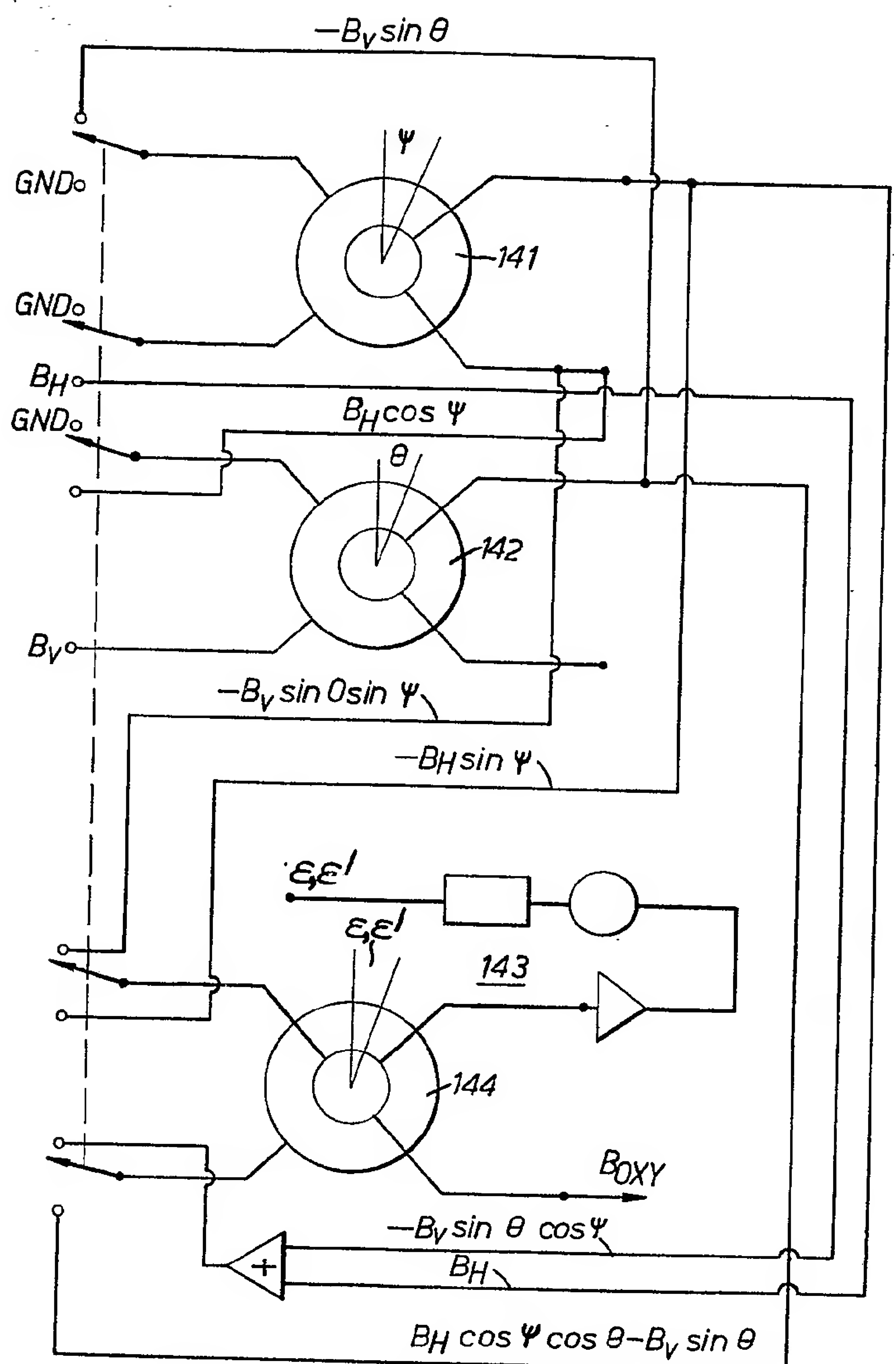
$-B_V \sin\theta$
ψ
GND
GND
141
B_H
GND
$B_H \cos\psi$
θ
142
B_V
$-B_V \sin\theta \sin\psi$
$-B_H \sin\psi$
$\varepsilon, \varepsilon'$
$\varepsilon, \varepsilon'$
143
144
B_{OXY}
$-B_V \sin\theta \cos\psi$
B_H
$B_H \cos\psi \cos\theta - B_V \sin\theta$

FIG. 14.

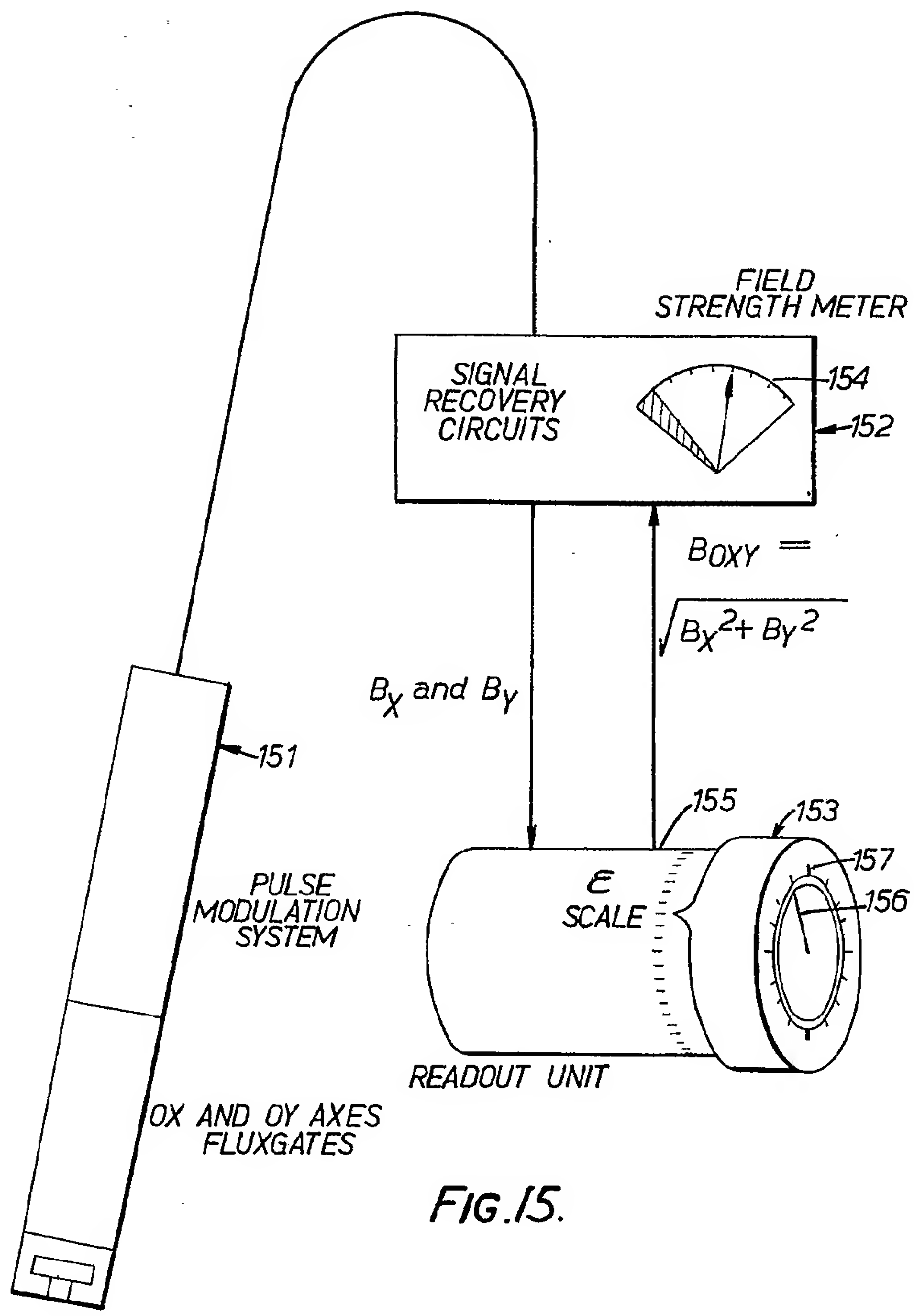
FIELD STRENGTH METER
SIGNAL RECOVERY CIRCUITS
154
152
$B_{OXY} = \sqrt{B_X^2 + B_Y^2}$
B_X and B_Y
151
155
153
157
156
PULSE MODULATION SYSTEM
ε SCALE
READOUT UNIT
OX AND OY AXES FLUXGATES

FIG. 15.